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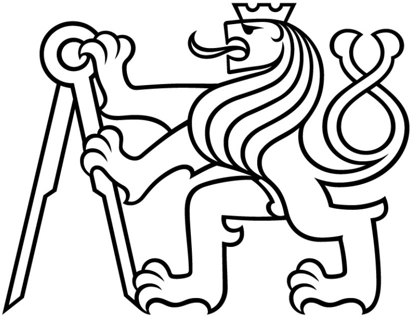
FACULTY OF MECHANICAL ENGINEERING



DOCTORAL THESIS STATEMENT

CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF MANAGEMENT AND ECONOMICS

DOCTORAL THESIS STATEMENT

ADVANCED VALUATION OF GRID-SCALE BATTERIES BASED ON REAL OPTIONS THEORY

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Ph.D. Programme: Mechanical Engineering

Branch of study: Enterprise Management and Economics

Primary doctoral advisor: prof. Ing. František Freiberg, CSc.

Doctoral dissertation statement for obtaining the academic title of “Doctor“, abbreviated to “Ph.D.“

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The doctoral dissertation was written in a combined form of study at the Department of Management and Economics of the Faculty of Mechanical Engineering of the CTU in Prague..

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before the Board for the Defence of the Doctoral Thesis in the branch of study Enterprise Management and Economics.

Those interested may get familiarised with the doctoral dissertation at the Department for Science and Research of the Faculty of Mechanical Engineering of the CTU in Prague, Technická 4, Praha 6.

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1. CURRENT STATE OF THE RESEARCH PROBLEM

The electrochemical electrical energy storage (EES) systems, more specifically the battery electricity storage systems (BESS), has been enjoying a substantial increase in popularity recently, due in part to their scalability [1].

BESS is predicted to gain the highest share of future growth in electricity storage capacity. By the end 2021, BESS capacity accounted for around 16 GW, and 6 GW of this capacity was added in the very same year [1].

This positive trend is reflected in the substantial research on valuation of BESS which is performed in two branches – one levering the standard valuation methods, and the other considering the real options analysis (ROA). Research of the first branch is based on the traditional discounted cash flow (DCF) methods such as net present value (NPV). Research of this branch focuses predominantly on the BESS dispatch problem. By solving the defined optimization problem (typically, profit is maximized, or costs are minimized), revenues are quantified, which are subsequently used as an input for the DCF method.

Profitability of the BESS investment is analyzed either in isolation or in combination with other energy assets. As an example, BESS can be coupled with a wind farm [2] or H_2 EES [3].

In order to maximize profitability of the BESS investment, authors consider multiple applications of BESS such as quality regulation, power bridging, and energy management [4], [5]. Especially energy management, including price arbitrage, enjoys high popularity as a research topic. Both spatial [6] and inter-temporal arbitrage has been considered in the recent research.

To exploit the price differentials on the market, various power markets such as the spot and reserve market have been considered. For example, Metz and Saraiva [6] analyze an investment in BESS used for price arbitrage in the 15- and 60-minute German spot market. Similarly, the authors in [7] used IRR to make an appraisal of BESS in seven (7) different US spot markets. All these authors come to the conclusion that the cost of BESS would need to decrease significantly to reach a break-even point, and justify the investment. As a reaction, some authors analyze deployment of BESS in the reserve market. However, authors such as Muche [8] disregard participation in the reserve market because it has lower liquidity and it is less transparent. This can be important when the proposed optimization model does not use known prices as an input but instead, a price forecast model is developed, which makes the study more realistic.

Research evolving in the second research branch does not perceive high initial costs and insufficient electricity price volatility as the only determinants of the low profitability of the BESS investments, and instead, they try to improve the approach to valuation of BESS investments by valuing uncertainty and flexibility inherent in this project type. By far, the most popular real option type in energy projects is the option to defer [9], but authors consider also other types of real options such as the option to abandon, option to switch [10], option to expand/contract, or the option to stage [11]. To value the identified real options, the authors use mostly one of the four real options valuation methods: partial differential equations, lattices, dynamic programming or simulations. By applying the real options valuation method, assumptions are accepted which are not always well communicated. No study has been identified which would analyze suitability of real options valuation methods to the BESS project.

2. GOALS OF THE DISSERTATION

The main goal of this dissertation is the **creation of an ROA-based framework for advanced capital investment valuation of BESS projects**.

To meet this goal, the following sub-goals are considered:

- Create an optimization program for a dispatch of BESS to maximize the NPV of the investment, which can then be used as one of the inputs for ROA.

- Consider popular ROA methods in the proposed valuation framework and provide a method for selecting the suitable method for valuation of a BESS project, based on specific valuation requirements.
- Verify functionality of the created framework through its application to a real-world business case.

Author’s hypothesis.

H1: The traditional DCF method undervalues investments in BESS projects, but results can be improved by applying ROA to value the uncertainty and flexibility inherent in these types of projects.

H2: Including the battery cost in the optimization program will significantly improve quality of the battery dispatch, which results in an improved NPV of the investment.

H3: Selection of a ROA method for a BESS project is a complex process that should be based on clear decision criteria, maximizing the probability that decision makers will accept the method’s results.

3. WORKING METHODS

The main research methods of the present study are a literature review, experiment, and case study. The literature review provides an overview of the existing methods and gaps in the research field, analyzing and synthesizing the collected scholarship in the context of the present study.

This dissertation employs both qualitative and quantitative data. The qualitative secondary data was collected in the form of literature review. Quantitative primary data came from the Energy Exchange of Austria (EXAA), which is used as the source for day-ahead prices of electricity [12].

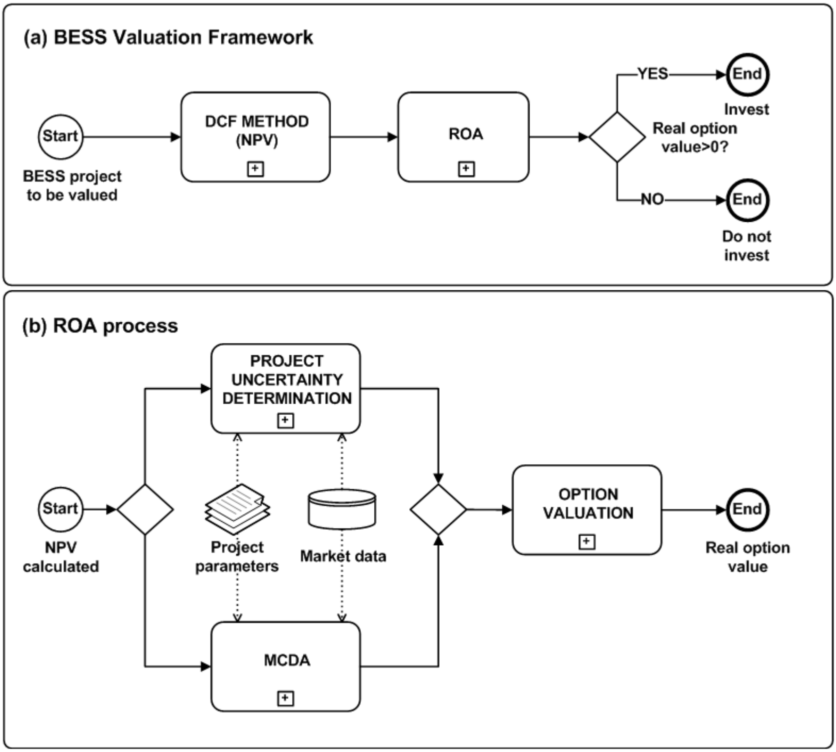

Fig. 1. BESS Valuation Framework: **(a)** High-level view of the valuation framework; **(b)** ROA process in detail.

In the experiment, causation between project value as a dependent variable and independent variables, such as battery parameters or electricity prices, are examined. An important part of the experiment is an optimal dispatch of the battery, an optimization problem which is defined as a MILP model. While the MILP model constitutes the first process of the proposed BESS Valuation Framework shown in Fig. 1, the real options analysis (ROA) constitutes the second following process of the Framework. The defined MILP model is developed within two scenarios; the BESS dispatch not constrained with battery degradation cost in the Scenario 1 is extended in the Scenario 2 by inclusion of the battery degradation cost with the goal of making the arbitrage more selective.

The degradation-cost-constrained model to maximize net cash flow from the operation of a BESS, introduced by Hurta et al. [13], is described in Eqs. (1)-(12). Eq. (1) maximizes the differences between cash inflow and cash outflow; cash inflow is provided by injecting the amount of energy $P_{OUT}(t)$ at the price $S(t)$ into the grid. On the other hand, cash outflow equals the amount of energy taken from the grid, multiplied by the spot price $S(t)$. The resulting net cashflow must be reduced by the degradation cost inflicted by the operation, which can be expressed as the product of the initial capital cost $CF(0)$ and the rate of degradation φ.

$$MAX \sum_{t=1}^{T} \left(S(t) \times \left(P_{OUT}(t) - P_{IN}(t) \right) \right) - CF(0) \times \varphi \tag{1}$$

Battery life loss must reflect both the fixed costs arising from continuous, calendar aging, as well as variable-cycle aging, conditional on the intensity of operation; both are incorporated with the variable φ, expressed in Eq. (2). While the former depends on the total time of operation ΔT and the calendar battery life RL, cycle aging tracks the number of theoretical cycles NoC completed within the operation time ΔT, out of the cycles *CL,* which constitute the total life of the battery [13].

$$\varphi \geq MAX \left(\frac{T}{RL}, \frac{NoC(T)}{CL} \right) \tag{2}$$

The power inflow $P_{IN}(t)$ and power outflow $P_{OUT}(t)$ cannot exceed the rated power of battery P_{MAX}, as ensured by the conditions in Eqs. (3)-(4). The binary variables $x(t)$ and $y(t)$ are introduced in Eq. (5) to avoid situations when the battery would be charged and discharged at the same time, which is not considered as feasible given the current technology available on the market [13].

$$0 \leq P_{IN}(t) \leq P_{MAX} \times \ x(t) \tag{3}$$

$$0 \leq P_{OUT}(t) \leq P_{MAX} \times y(t) \tag{4}$$

$$x(t) + y(t) \leq 1 \begin{cases} charging: x(t) = 1, y(t) = 0 \\ discharging: x(t) = 0, y(t) = 1 \end{cases} \tag{5}$$

Eq. (6) ensures that the battery's level of charge $\mathrm{C(t)}$ is neither negative nor exceeds its rated capacity, $\mathrm{C_{MAX}}$, lowered by the depth of discharge *DOD.*

$$(1 - DOD)C_{MAX} \leq C(t) \leq C_{MAX} \tag{6}$$

The level of charge $C(t)$ of the battery is brought into relation with the power inflow $P_{IN}(t)$ and power outflow $P_{OUT}(t)$ in Eq. (7):

$$C(t) - C(t-1) = \left(P_{IN}(t) \times \sqrt{\varepsilon}\right) + \left(P_{OUT}(t) \times \left(\sqrt{\varepsilon}\right)^{-1}\right), \quad where, t \in [2, T] \tag{7}$$

where, ε stands for the round-trip efficiency of the battery.

Eq. (8) ensures that the BESS's level of charge $C(t)$ is 0 at the beginning of the operation; thus, the first operation of the battery is charging.

$$C(1) = 0 \tag{8}$$

In the next step, the DCF method is applied to calculate the NPV of the investment, as expressed in Eq. (9):

$$NPV = -CF(0) + \sum_{t=1}^{T} \frac{CF(t)}{(1+r)^t} \tag{9}$$

where, *r* is the discount factor.

The method takes the net cash flow $CF(t)$ and the initial capital outlay $CF(0)$ as inputs. These are expressed in Eq. (10) and Eq. (11), respectively. The initial capital outlay multiplies the investment cost *I* with the greater value of the calendar and cycle degradation, *T/RL* and *NoC(T)/CL*, respectively.

$$CF(t) = \sum_{t=1}^{T} \left(S(t) \times \left(P_{OUT}(t) - P_{IN}(t) \right) \right) \tag{10}$$

$$CF(0) = I \times MAX\left(\frac{T}{RL}, \frac{NoC(T)}{CL} \right) \tag{11}$$

where, RL is the battery calendar life, CL is the battery cycle life, and $NoC(T)$ is the number of theoretical cycles performed within ΔT, as expressed in Eq. (12):

$$NoC(T) = \frac{\sum_{t=1}^{T} \left[\left(P_{IN}(t) \times \sqrt{\varepsilon} \right) + \left(P_{OUT}(t) \times \left(\sqrt{\varepsilon} \right)^{-1} \right) \right]}{2 \times C_{MAX} \times DOD} \tag{12}$$

Applying the defined MILP problem to longer periods ΔT can require long computation times. To overcome this problem, and shorten the computation time, the MILP problem is divided into a series of MILP sub-problems, as described by Metz and Saraiva [6], and applied by Hurta et al. [13]. The model is solved with the use of PuLP library in the Python programming language.

The output of the degradation-cost-constrained model is used as an input in the other process of the Framework – ROA. This process consisting of two sub-processes – the project uncertainty determination and the multiple criteria decision analysis (MCDA). Major emphasis is laid on the latter sub-process used for selection of the suitable real options valuation model applied for the BESS investment; Hurta [14] proposed seven assessment criteria to select the suitable ROA valuation method for a project in the energy sector which are further extended to propose the following criteria:

- Expected acceptance by management.
- Early exercise.
- Negative prices.
- Time horizon.
- Volatility.

- Ability to value popular types of real options.
- Number of sources of uncertainty.
- Speed of option value calculation.

By applying MCDA and the set of the proposed assessment criteria, the real options valuation method most suitable for the BESS investment can be selected, and used.

Based on the literature review, three most popular valuation techniques are considered as alternatives: Black-Scholes model (BSM), Cox-Ross-Rubinstein binomial model (CRRM) and Monte-Carlo simulation (MCS). The NPV of the BESS investment calculated in the first process of the Framework is extended with the real option value which provides an extended valuation of the BESS project, and enables to make an investment decision considering both uncertainty and flexibility inherent in this type of project.

Case study methodology is used not only to demonstrate the functionality of the proposed valuation framework with real-world data, but also to help answer the defined research questions, and ultimately leads to either accepting or rejecting the defined hypotheses. The real-world Case study assumes the company ‘Energy4’ is considering an investment in the $LiFePO_4$ BESS, used for price arbitrage in the day-ahead market for electricity at the end of the year 2020. The company can reserve the necessary resources until the year 2025, and it possesses the flexibility to provide those resources to invest in any year until 2025. The proposed BESS Valuation Framework is applied to value the investment, and to make a decision on the investment. The size of the initial capital outlay is set to 345 USD/kWh, which was a valid cost level for the year 2020 [15]. To perform MCDA and select the most appropriate real options valuation method for the BESS project, five experts were selected to act on behalf of the model company.

4. RESULTS

DCF process – BESS dispatch problem

The results of the DCF process are divided into Scenario 1 (MILP model without degradation process), and Scenario 2 (MILP model with degradation process). Net cashflow and cumulative NPV from a BESS dispatch are plotted in the Fig. 2 (BESS dispatch ignoring the battery degradation process) and in the Fig. 3 (BESS dispatch enhanced with the battery degradation process). The results in a tabular form are provided in Tables 1-2. The key driver of cycle degradation is DOD, thus sensitivity of the model to this variable is evaluated in Scenario 2.

When comparing Fig. 3a with Fig. 2a, it is clear that net cashflow has decreased significantly, peaking at 841 EUR in September in Scenario 2, instead of 1460 EUR in Scenario 1. However, the more selective dispatch has been positively rewarded by the increase of NPV, as can be seen by comparing Figs. 3b and 2b. While NPV totaled at -86566 EUR in Scenario 1, NPV significantly improved in Scenario 2, reaching the value of - 15635 EUR (for 60% DOD).

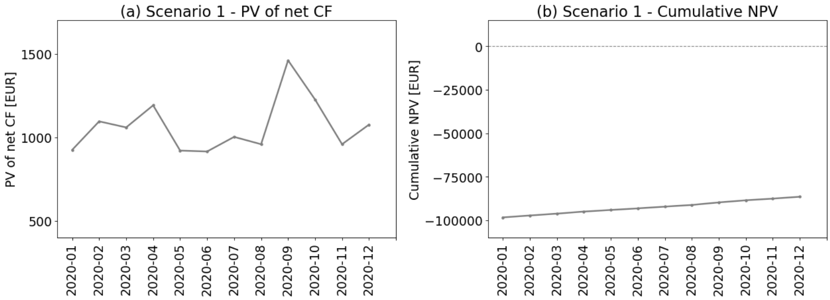

Fig. 2. Scenario 1 – Discounted net cashflow and cumulative NPV from a BESS dispatch ignoring the battery degradation process in the dispatch model.

Table 1. Scenario 1 – Results of the BESS dispatch.

Parameter	**Value**
Accumulation [MWh]	806
Generation [MWh]	774
Sum of PV net CF [EUR]	12794
NoC(T)	748
NoC(T)/CL	0.288
T/RL	0.067
NPV [EUR]	-86566

When evaluating sensitivity of the model to *DOD*, the highest NPV has been generated when dispatching the battery at 60% *DOD*. This finding is in line with the conclusions of Hurta et al. [105], and it stems from the typical pattern in the selected day-ahead prices with two peaks a day.

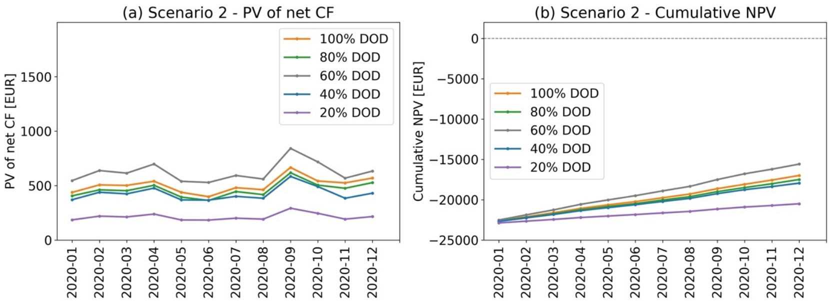

Fig. 3. Scenario 2 – Discounted net cashflow and cumulative NPV from a BESS dispatch respecting the battery degradation process in the dispatch model. Sensitivity of the dispatch model to *DOD*.

Obviously, when battery degradation process was not part of the defined MILP, the BESS was dispatched at high frequency, which is reflected in (among other factors) the relatively higher accumulation and generation in Scenario 1; the cycle degradation (*NoC(T)/CL*) exceeded the calendar degradation (*T/RL)*, which proved to be economically unjustifiable, looking at the negative NPV.

Table 2. Scenario 2 – Sensitivity of the dispatch model to *DOD*.

	DOD 20%	DOD 40%	DOD 60%	DOD 80%	DOD 100%
Accumulation [MWh]	162	322	402	160	159
Generation [MWh]	155	310	387	153	152
Sum of PV net CF [EUR]	2561	5121	7480	5569	6069
NoC(T)	761	754	626	188	149
NoC(T)/CL	0.022	0.038	0.062	0.058	0.057
T/RL	0.067	0.067	0.067	0.067	0.067
NPV [EUR]	-20554	-17994	-15635	-17546	-17046

After the introduction of the battery degradation process in Scenario 2, the MILP model has substantially improved financial expectations from the investment.

In the next step, sensitivity of the model to the size of investment costs is analyzed. Five different investment costs are considered. The highest investment costs, the baseline scenario, are 345 USD/kWh. In the following sensitivity scenarios, the investments costs are reduced up to 10 EUR/kWh. For the sensitivity analysis, 100% *DOD* is selected to enable comparison of the results also with Scenario 1. The results are presented in Fig. 4 and Table 3. As the investment costs decrease, the frequency of dispatch goes up, which results in the increase of accumulation, generation, sum of cashflow, number of cycles and cycle degradation. In the last sensitivity scenario (10 USD/kWh), the value of cycle degradation exceeds the calendar degradation, and it approaches the value from Scenario 1, but in contrast to Scenario 1, the increase in the degradation is justified by the positive NPV.

The last two sensitivity scenarios (50 USD/kWh and 10 USD/kWh) resulted in a positive NPV, unlike the third sensitivity scenario (100 USD/kWh) with NPV close to the NPV breakeven point. To determine the breakeven point, the input investment costs are stepwise changed by the unit of 1 USD/kWh in the model to identify the first occurrence of investment costs generating a positive NPV. By this procedure the breakeven point is identified at 98 USD/kWh.

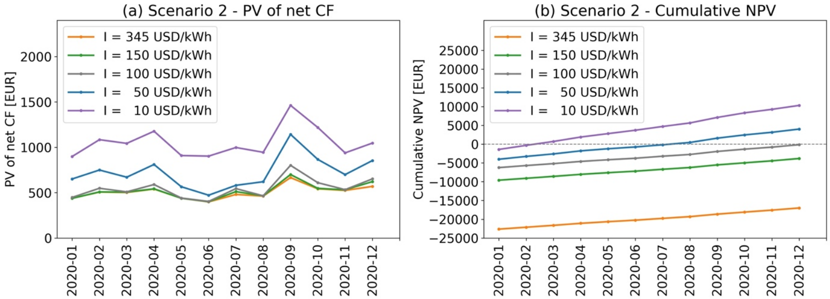

Fig. 4. Scenario 2 – Discounted net cashflow and cumulative NPV from a BESS dispatch respecting the battery degradation process in the dispatch model. Sensitivity of the dispatch model to investment costs.

Table 3. Scenario 2 – Sensitivity of the dispatch model to investment costs.

	345 USD/kWh	150 USD/kWh	100 USD/kWh	50 USD/kWh	10 USD/kWh
Accumulation [MWh]	159	161	168	259	642
Generation [MWh]	152	153	161	248	617
Sum of PV net CF [EUR]	6069	6212	6546	8684	12625
NoC(T)	149	151	158	242	597
NoC(T)/CL	0.057	0.058	0.061	0.093	0.230
T/RL	0.067	0.067	0.067	0.067	0.067
NPV [EUR]	-17046	-3838	-154	4034	10325

The sensitivity analysis of the model to investment costs confirmed the model is sensitive to the size of investment costs. Reduction of the initial capital outlay led *ceteris paribus* to a more frequent dispatch of the BESS, and to an increase of NPV. While the increase of the dispatch frequency was rather subtle until the NPV breakeven point, the sensitivity to investment costs has significantly increased when there was an incentive in the form of a positive NPV, i.e., beyond the NPV breakeven point.

ROA – MCDA

MCDA is used to select a suitable valuation model for the identified American call option. Of the three methods described in the Study, Saaty's method is selected for criteria weighting. In contrast to the Scoring method, it makes comparisons between all the criteria. Because it also enables expressing the size of the preference, Saaty's is preferred to Fuller's triangle, and was also selected as the preferred method for ranking of alternatives and for determining the weights of the experts. This choice is in line with the high popularity of the Saaty's method as an MCDA technique [16], [17].

The resulting ranking of the three considered alternatives, namely BSM (A_1), CRRM (A_2) and MCS (A_3) is presented in Table 4. Based on the achieved scores, CRRM (A_2) is the most preferred method, followed by MCS (A_3) and BSM (A_1).

Table 4. Scores Z_i of the alternatives, and the resulting ranking.

	A_1	A_2	A_3
z_1^i	0.173	0.534	0.293
z_2^i	0.204	0.578	0.218
z_3^i	0.288	0.430	0.282
z_4^i	0.293	0.399	0.308
z_5^i	0.239	0.409	0.352
z_6^i	0.258	0.365	0.377
z_7^i	0.320	0.447	0.233
z_8^i	0.539	0.284	0.177
Z_i	0.250	0.471	0.279
Ranking	3	1	2

ROA – CRRM

The results from Scenario 2 were used as inputs for Scenario 3 to calculate the value of waiting, and to determine the optimal timing of the investment.

To construct CRRM, it was necessary to first determine the volatility σ of the project's cash flow. MCS was deployed to simulate the cash flow. The mean-reverting model (MRM) was selected as the model for the price, since it enables to model both negative prices and daily seasonality. A total of 1000 simulations were performed to generate the expected future realizations of the price.

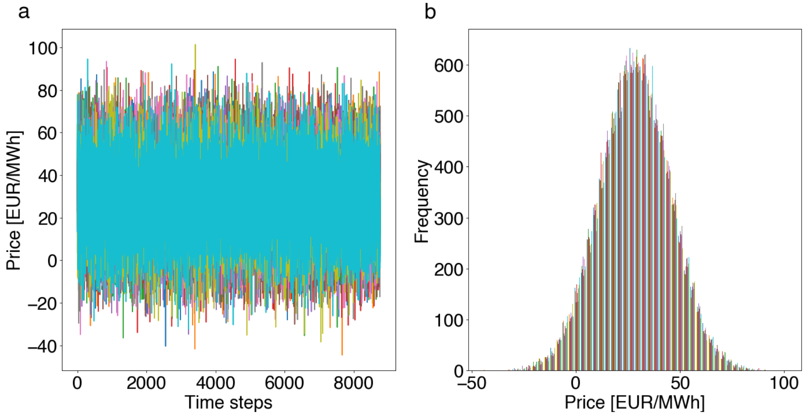

Fig. 5. Simulations (totaling 1000) of the day-ahead price based on MRM: **(a)** Price plot of 10 simulations; **(b)** Histogram of 10 simulations.

Prices of 8760 hourly contracts, which equals the length of one year, are simulated. Ten (10) out of the 1000 simulations performed are plotted in Fig. 5.

The prices simulated in the preceding step were used for calculating the net cash flow in Scenario 3. Ten (10) plots out of the 1000 simulations for Scenario 3 are plotted in Fig. 6

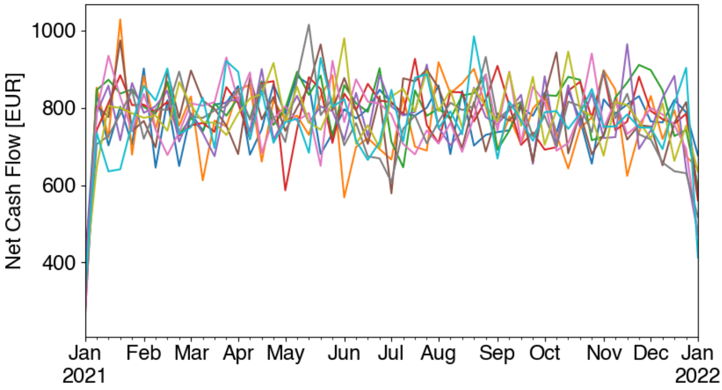

Fig. 6. Scenario 3 – Net Cash Flow of 10 out of the 1000 simulations.

In Scenario 3, σ_W calculated from the resulting weekly data equals 0.2050, so the annualized value σ equals 1. 1.4783.

The volatilities of project cash flow calculated in the preceding step are used for construction of the CRRM

In neither case it is optimal to call the option prior to its termination date. In other words, the value of holding the option is higher than executing it, which holds true for all time points prior to the terminal nodes. Thus, given the market situation, the company should use its flexibility to postpone the investment until the end of the four-year period, regardless of the size of the initial capital costs. As can be seen in Fig. 7, the company can abandon the investment plans prior to the year 2025, when the market evolves in an unfavorable direction, and direct the resources into different, more profitable, projects.

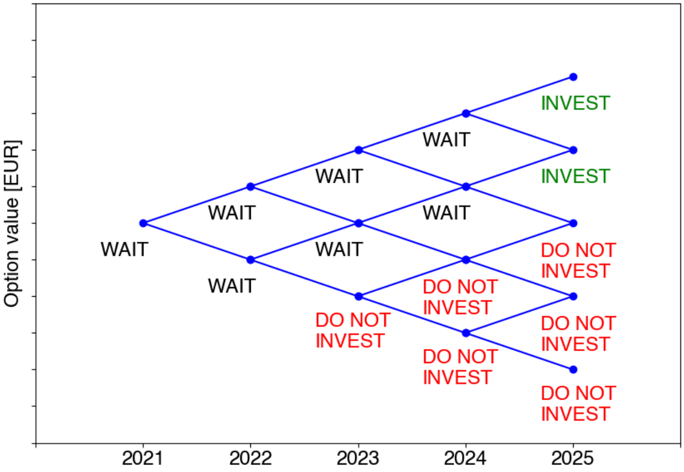

Fig. 7. Scenario 3 – Decision on the investment.

5. CONCLUSIONS

Evaluation of research questions

The dissertation provides answers to the three defined research questions.

Q1: "Can ROA be recommended as an extension of the traditional DCF method for valuation of investments in BESS projects?"

ROA proved to be a capable tool for evaluating the uncertainty and flexibility inherent in BESS projects in both the literature review and the case study. Because the traditional DCF method excludes these two factors, it can undervalue a BESS project. The effect was striking, especially in the case study when comparing Scenario 2 with Scenario 3. When counting solely on NPV, the investment would be unlikely to earn management approval, given the negative NPV value. Valuation of the very same investment using ROA showed potential for the investment, given the high volatility on the day-ahead market. The chance that the market will evolve in a favorable direction is of value, especially when management has the power to reject the investment when the opposite situation arises. For the above reasons, BESS projects should be always valued with *both* the DCF method and ROA.

Q2: "What is the impact of initial capital cost on dispatch of the battery, and on the resulting value of the investment?"

As confirmed by the preceding case study (Section 11), lower initial costs lead, *ceteris paribus,* to a higher frequency of dispatch for BESS, reflected in the higher NPV value as shown in Scenario 2. The sensitivity to investment costs has significantly increased beyond the NPV breakeven point.

Q3: “What assessment criteria can be used for selection of ROA method used for capital investment valuation of BESS project out of the existing ROA methods?

Eight assessment criteria have been proposed: expected acceptance by management, early exercise, negative prices, time horizon, volatility, ability to value popular types of real options, number of sources of uncertainty, and speed of option value calculation. These assessment criteria help facilitate the process of selecting a ROA model for valuation of a BESS project.

Evaluation of goals of the dissertation

The main goal of this dissertation, namely **creation of an ROA-based framework for advanced capital investment valuation of BESS projects,** has been achieved in Sections 3-8 of the dissertation thesis. Functionality of the framework has been verified by performing the case study.

The sub-goals supporting the main goal have been achieved as follows:

- Create an optimization program for a dispatch of BESS to maximize the NPV of the investment, which can then be used as one of the inputs for ROA.

  The program for dispatch of a BESS was defined with two versions of the MILP model, where the initial MILP maximizing net cash flow of a project was extended with a battery-degradation process in the second, more advanced, MILP. The extended version of the model was subsequently used as an input for ROA in the case study.

- Consider popular ROA methods in the proposed valuation framework and provide a method for selecting the suitable method for valuation of a BESS project, based on specific valuation requirements.

  MCDA was proposed as a suitable selection method. Eight assessment criteria were determined, based on the in-depth literature review, and defined as follows: expected acceptance by management, early exercise, negative prices, time horizon, volatility, ability to value popular types of real options, number of sources of uncertainty, and speed of option value calculation. These eight assessment criteria have been combined with three alternatives, representing the most popular ROA models: BSM, CRRM and MCS. This combination was used to create a decision matrix which can easily be re-used and applied to any specific conditions and requirements to value a BESS project.

- Verify functionality of the created framework through its application to a real-world business case.

  The case study confirmed that the proposed valuation framework is functional and that it can be used to:

    - Calculate NPV value of BESS project considering the battery degradation process.
    - Select an ROA method for a BESS project which best meets the specific conditions and requirements of the valuation process.
    - Calculate the value of uncertainty and flexibility inherent in a BESS project.

Evaluation of author’s hypotheses

H1: The traditional DCF method undervalues investments in BESS projects, but results can be improved by applying ROA to value the uncertainty and flexibility inherent in these types of projects.

The review of the literature on ROA applied to BESS projects in Section 4.1 showed that ROA can really improve the value of the investment, and that counting solely on the traditional methods such NPV could have otherwise led to rejecting the investment.

The case study in Section 11 demonstrated that valuation of a BESS project relying solely on the DCF method undervalues the project and confirms the findings from the literature review. In Scenario 1, the project was unable to reach a positive NPV, generating NPV of only -86566 EUR.

In Scenario 2, incorporation of the degradation process improved the project value significantly, resulting in the NPV of -15635 EUR for 60% *DOD*, and identified the NPV breakeven point for 100% *DOD* at 98 USD/kWh. By deploying ROA in Scenario 3, the project value increased even more, showing the positive value of waiting. Given that management possess flexibility to defer the project, the value of waiting in Scenario 3 equals 21653.33 EUR. By postponing the investment until 2025, management can profit from the high uncertainty on the market and realize a positive value for the company.

These findings enable the acceptance of the H1 hypothesis and confirm the significant role of ROA in the valuation of BESS projects. By extending the NPV method with ROA, practitioners can avoid situations where BESS projects are undervalued, and thus rejected.

H2: Including the battery cost in the optimization program will significantly improve quality of the battery dispatch, which results in an improved NPV of the investment.

Hypothesis H2 can be accepted based on the findings of Scenarios 1 and 2 in the case study; in the MILP model, failing to consider the impact of the dispatch on the degradation of the BESS led to high net cashflow. However, after assessment of the battery life loss as a direct impact of the arbitrage, the BESS investment resulted in a significantly negative NPV. In Scenario 2, net cashflow was balanced with the degradation effect of the BESS, to determine the optimal dispatch strategy. This approach provided a positive effect on NPV, which generated an improved NPV in Scenario 2, and provided a firm ground for valuation in Scenario 3. The sensitivity analysis of the model to investment costs confirmed the model is sensitive to the size of investment costs. Reduction of the initial capital outlay led *ceteris paribus* to a more frequent dispatch of the BESS, and to an increase of NPV. While the increase of the dispatch frequency was rather subtle until the NPV breakeven point, the sensitivity to investment costs has significantly increased when there was an incentive in the form of a positive NPV, i.e., beyond the NPV breakeven point.

H3: Selection of a ROA method for a BESS project is a complex process that should be based on clear decision criteria, maximizing the probability that decision makers will accept the method's results.

Comprehensive literature review on both ROA and BESS has been conducted. Compared to other projects, the BESS projects have some specifics which have been addressed in the review. The output of the literature review enabled to propose the set of eight assessment criteria which help to facilitate the selection process. Acceptance of the proposed assessment criteria has been positively tested in the MCDA.

Without clear assessment criteria, a less-suitable ROA method could be chosen for valuation of a BESS, which would inevitably lead to a less accurate estimate and a lower probability of getting a buy-in from the decision makers. All of these findings support accepting H3.

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List of candidate's publications relating to the dissertation thesis

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Publications in peer-review journals

Hurta, A. (2023). Real Options Analysis in The Energy Sector with A Focus on The Spot Price of Electricity: Decision Criteria for Selecting the Optimal Method. *International Journal of Advanced Research in Engineering and Technology, 14*(1), 1-32. https://doi.org/10.17605/OSF.IO/7VPDY.

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ABSTRACT

The liberalization of the energy sector and the continuous development of intermittent renewable energy sources (RES) has promoted advanced approaches to energy storage. Battery energy storage systems (BESS) offer satisfactory parameters of storage; however, high initial capital cost has been restricting more significant spread of the technology. The effect of high capital cost is worsened by the inadequate valuation processes used for this type of investment. BESS projects are implemented under high uncertainty, stemming mainly from high volatility of energy prices. At the same time, management typically possesses flexibility when it comes to the scope and timing of BESS projects. Traditional discounted cashflow (DCF) methods do not recognize these aspects properly, which can lead to undervaluation of the project. Real options analysis (ROA) recognizes both uncertainty and flexibility inherent in these types of projects, and offers an enhanced method of valuation. However, the ROA approach cannot be perceived as a complete substitute for the traditional DCF method, but rather as its extension.

This dissertation recognizes importance of both the DCF and ROA methods, and develops a valuation framework covering both approaches, designated specifically for BESS projects. The DCF method is based on a robust, mixed-integer linear programming (MILP) model, which maximizes net cashflow generated by deploying a BESS for arbitrage on the day-ahead market. The MILP model is solved without considering the degradation process of the BESS in the first Scenario, which leads to an extensive degradation of the BESS. As a result, the investment in a BESS under current market conditions cannot be justified, when valued with net present value (NPV). In the second step, the initial MILP model is extended with a degradation process, which ensures that the battery dispatch balances net cashflow with degradation cost. The improvement in the pattern of dispatch is reflected in a significant improvement in NPV, as demonstrated by the case study in Section 11 in Scenario 2.

In the third step, ROA is introduced to extend the NPV value from the preceding step with the value of uncertainty and flexibility inherent in a BESS project. A literature review of ROA in the field of BESS projects provides the grounds for deploying a multiple-criteria decision analysis (MCDA) in the next step. Eight decision criteria are proposed, based on extensive research in the field, in order to facilitate selection of the suitable ROA method. The created valuation framework enables practitioners to select the ROA method which best meets specific valuation requirements. The valuation framework is applied in a case study, where the Cox-Ross-Rubinstein binomial option pricing model (CRRM) received the highest score out of the three ROA methods considered. For calculating the volatility of a project, simulation of future project cashflow is demonstrated as a useful alternative to other methods, such as implied volatility determined on a derivatives market, or volatility predicted with (Generalized) Auto Regressive Conditional Heteroskedasticity (G)ARCH family models. The case study shows the positive value of postponing the investment in a BESS project, and shows that even a BESS project with negative NPV can have a positive value, when being valued with ROA. Most importantly, it confirms the functionality and benefits of the proposed BESS valuation framework.

RÉSUMÉ

Liberalizace energetického sektoru a pokračující rozvoj občasných obnovitelných zdrojů energie (renewable energy sources - RES) podpořily pokročilé přístupy ke skladování energie. Bateriové systémy skladování energie (battery energy storage systems - BESS) nabízejí vyhovující parametry skladování; vysoké počáteční kapitálové náklady však omezují výraznější rozšíření technologie. Efekt vysokých kapitálových nákladů je zhoršován neadekvátními metodami oceňování používanými pro tento typ investice. Projekty BESS jsou realizovány za vysoké nejistoty pramenící především z vysoké volatility cen energií. Management má zároveň obvykle flexibilitu, co se týče rozsahu a načasování projektů BESS. Tradiční metody diskontovaných peněžních toků (discounted cashflow - DCF) tyto aspekty nedostatečně zohledňují, což může vést k podhodnocení projektu. Analýza reálných opcí (real options analysis - ROA) zohledňuje nejistotu i flexibilitu, která je tomuto typu projektů vlastní, a nabízí pokročilý způsob oceňování. Přístup ROA však nelze vnímat jako substitut tradiční metody DCF, ale spíše jako její komplement

Tato disertační práce respektuje význam jak metody DCF, tak metody ROA, a navrhuje model pro oceňování zahrnující oba přístupy, určený speciálně pro projekty BESS. Metoda DCF je založena na robustním modelu smíšeného celočíselného lineárního programování (mixed-integer linear programming - MILP), který maximalizuje čistý peněžní tok generovaný využitím BESS pro cenovou arbitráž na spotovém trhu. V prvním scénáři je model MILP řešen bez zohlednění procesu degradace, což vede k rychlé degradaci BESS. V důsledku toho nelze investici do BESS oceněnou pomocí čisté současné hodnoty (net present value - NPV) za současných podmínek na spotovém trhu ospravedlnit. Ve druhém kroku je počáteční model MILP rozšířen o proces degradace, který zajišťuje, že je při použití BESS pro cenovou arbitráž čistý peněžní tok porovnáván s náklady degradace. Na případové studii je ukázáno, že takto vylepšená strategie arbitráže se odráží ve významném navýšení hodnoty NPV.

Ve třetím kroku je využita metoda ROA s cílem hodnotu projektu vyjádřenou pomocí NPV určené v předchozím kroku dále rozšířit o hodnotu nejistoty a flexibility vlastní projektu BESS. Přehled literatury o ROA v oblasti projektů BESS poskytuje základ pro nasazení

vícekriteriální rozhodovací analýzy (multiple-criteria decision analysis - MCDA) v dalším kroku. S cílem usnadnit výběr optimální metody ROA je navrženo osm rozhodovacích kritérií. Vytvořený rámec pro oceňování umožňuje vybrat metodu ROA, která nejlépe splňuje konkrétní požadavky na oceňování. Rámec oceňování je aplikován v případové studii, ve které Cox-Ross-Rubinsteinův binomický model oceňování opcí (Cox-Ross-Rubinstein binomial option pricing model - CRRM) získal nejvyšší skóre ze tří uvažovaných metod ROA.

Pro výpočet volatility projektu je použita simulace, která je považována za smysluplnou alternativu k jiným metodám výpočtu volatility jako je implikovaná volatilita určená na trhu s deriváty nebo volatilita predikovaná pomocí modelů podmíněné heteroskedasticity typu (G)ARCH (Generalized Auto Regressive Conditional Heteroskedasticity). Případová studie potvrzuje kladnou hodnotu odložení investice do projektu BESS a ukazuje, že i projekt BESS s negativní NPV může mít kladnou hodnotu při oceňování pomocí ROA, a co je nejdůležitější, potvrzuje funkčnost a výhody navrhovaného oceňovacího rámce BESS.